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Residue management and paratillage effects on some soil properties and rain infiltration

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Abstract

Dryland winter wheat (*Triticum aestivum* L.) and grain sorghum [*Sorghum bicolor* (L.) Moench] are often grown on the semiarid North American Great Plains using the wheat–sorghum–fallow (WSF) crop rotation. When used with WSF, no-tillage (NT) and stubblemulch tillage (SM) residue management reduce evaporation and increase yield, but more runoff occurs with NT compared to SM. Our objectives were to determine the effects of NT and SM residue management with paratill (PT) and sweep (ST) tillage on soil properties and rain infiltration into a Pullman clay loam (US soil taxonomy: fine, mixed, superactive, thermic Torrertic Paleustoll). Six contour-farmed level-terraced watersheds were dryland cropped using a WSF rotation with each phase of the WSF appearing all years as main plots. Residue management by tillage subplots of: (i) NT with PT, (ii) NT with NOPT, (iii) NT with ST, (iv) SM with PT, and (v) SM with NOPT were installed within these main plots after sorghum harvest. Approximately, 9 months later during the wheat phase (before planting), we measured selected soil characteristics and the infiltration rate and amount using a rotating disk rain simulator that applied cistern stored rainwater at 48 mm h^{-1} on the five tillage—residue management treatments. Cumulative infiltration at 1 h was similar among tillage treatments within residue management practices, i.e., infiltration into SM plots averaged 32.4 ± 3.9 mm compared to 21.9 ± 2.5 mm for NT plots. Regardless of residue management, PT and ST tillage caused no significant ($P < 0.05$) increase in infiltration compared to NOPT. Measured cone-penetrometer resistance, bulk density, and initial soil-water content decreased with ST and PT for NT residue management but not SM residue management. The data show that SM residue management compacted the soil beneath, the sweep implements; thus, negating any benefits of reduced soil bulk density and penetration resistance with PT. We conclude that reductions in soil density and penetration resistance due to PT were diminished by SM tillage and that infiltration was regulated at the soil surface by a rapidly forming crust, which negated PT effects on SM or NT. Published by Elsevier Science B.V.

Keywords: No-tillage; Stubble mulch tillage; Infiltration; Penetration resistance; Crop rotation

1. Introduction

Fallow (noncropped) periods are used on the semiarid North American Great Plains to increase storage of precipitation as soil water so that winter wheat (*Triticum aestivum* L.) and grain sorghum [*Sorghum bicolor* (L.) Moench] can be grown without irrigation. Jones and Popham (1997) describe a wheat–sorghum–fallow (WSF) rotation that produces two crops, sorghum and wheat, with intervening 11-month fallow periods during a 3-year cycle (Fig. 1). The water conservation benefits of using the WSF crop rotation

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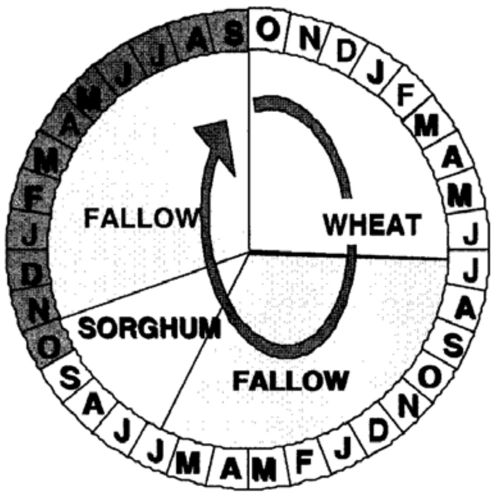

Fig. 1. The WSF rotation diagramed as a 3-year cycle beginning with wheat establishment in October (top). Wheat is harvested 10 months later in July and the soil is fallowed until June of the second year (11 months) when grain sorghum is grown using soil water stored during fallow to augment summer rainfall. After sorghum harvest in November of the third year, the soil is again fallowed for 10 months when wheat is planted and the cycle repeated.

have been further improved by applying residue retaining management practices; thus, achieving steadily greater grain sorghum yields (Unger and Baumhardt, 1999).

The residue retaining management practices that use stubblemulch tillage (SM) and no-tillage (NT) are effective means of reducing evaporation and conserving precipitation (Steiner, 1994). Under dryland conditions, however, both wheat and sorghum produce limited grain and residue yields. Residue amount is often inadequate to intercept raindrop impact and prevent the formation of soil crusts (Baumhardt et al., 1993). Water infiltration into soil managed with NT is typically lower than with SM, which fractures soil crusts and reduces storm runoff (Jones et al., 1994). Residue management and tillage practices that limit evaporation and maintain infiltration on clay loam soils may contribute towards increased water conservation and crop production levels.

While soil crusts are fractured with SM, some residues (15–5%) are also incorporated. Paraplow tillage (PT) loosens the soil without incorporating surface residues and increases soil porosity and root and water penetration (Mukhtar et al., 1985; Busscher et al., 1988). Unger (1993) reported a similar initial reduction in soil density and penetration resistance to a depth of 0.3 m with PT on a Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll) compared to NT plots for up to 4 years, but the benefits of infrequent PT were not retained consistently. Pikul and Aase (1999) reported no differences in wheat yields due to PT of sandy loam soils, but both soil properties and cumulative infiltration of simulated rain benefited from residual effects for 2.5 years. Cumulative infiltration was increased with PT under ponded conditions (Mukhtar et al., 1985; Clark et al., 1993), but we found no reports characterizing PT effects on rain infiltration into clay loam soil.

We hypothesized that PT performed every 3 years (following sorghum harvest) would destroy soil crusts, roughen the soil surface, and increase infiltration on NT managed fields. Our research objectives were to determine the effects of PT and ST on soil properties and infiltration of simulated rainfall into a clay loam soil with SM or NT residue management under dryland conditions.

2. Materials and methods

2.1. Experimental

Tillage and residue management effects on soil physical properties and the infiltration of simulated rainfall were evaluated at the USDA-Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, TX (35°11′N, 102°5′W), using six contour-farmed level-terraced watersheds. These watersheds, described by Hauser et al. (1962), range in area from 2.3 to 4.1 ha and have a gently sloping (1–2%) Pullman clay loam (Unger and Pringle, 1981). They were cropped in a WSF rotation with each phase of the WSF sequence present as main plots in two watersheds each year. Winter wheat, TAM 107[1] (Foundation Seed, College Station, TX), was sown on all wheat plots in late September or early October at a 40 kg ha^{-1} rate to achieve 2.5×10^6 plants ha^{-1} using

[1] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service. Mention of a pesticide does not constitute a recommendation for use nor does it imply registration under FIFRA as amended.

a high-clearance grain drill with hoe openers and press wheels at a 0.3 m row spacing. Grain sorghum, Dekalb hybrid "DK41Y" (DeKalb, IL), was seeded in rows 0.75 m apart during early to mid-June at 80,000 seed ha^{-1}, using 'Max-Emerge™' (John Deere, East Moline, IL) unit planters. Growing season weed control for sorghum consisted of 1.7 kg a.i. ha^{-1} propazine [6-chloro-*N*,*N*′-bis(1-methylethyl)-1,3,5-triazine-2,4-diamine] applied pre-emergence. Control of flixweed [*Descurainia sophia* (L.) Webb ex Prantl] in growing wheat required 0.6 kg a.i. ha^{-1} 2,4-D [(2,4-dichlorophenoxy) acetic acid] applied in late February during some years.

These three paired-watersheds received SM or NT residue management. With SM, weeds were controlled as needed during the fallow season (about four operations) using a 4.6 m-wide Richardson (Sunflower Man, Beloit, KS) sweep plow at a depth of 0.10 m, which had one 1.5- and two 1.8 m-wide overlapping V-shaped blades plus an attached mulch treader. Under NT, weeds were chemically controlled (Table 1), resulting in no soil disturbance, except for seeding the crops. During the fallow after sorghum harvest phase of this 3-year WSF rotation, paratillage (PT) and no-paratillage (NOPT) were applied to 35 m × 40 m plots beginning in 1988; therefore, paratillage was applied every 3 years to plots in any paired-watersheds. The paratillage implement (Tye, Lockney, TX), consisting of four center faced paratill shanks with residue cutting coulters mounted on a tool bar so that the points appeared at 0.6 m intervals, was operated at 1.3 m s^{-1} and 0.35 m depth. An additional one-time sweep tillage treatment (ST) was applied to, otherwise, NT residue management plots during the fallow after sorghum phase of the 3-year WSF rotation sequence. The resulting residue management and tillage treatments of: (i) NT with PT, (ii) NT with NOPT, (iii) NT with ST, (iv) SM with PT, and (v) SM with NOPT were replicated three times within paired-watersheds. Measurements were compared according to a randomized complete block analysis of variance using SAS-PROCGLM (SAS, 1988).

2.2. Infiltration

Infiltration was measured in September 1991, approximately 9 months after paratillage, near the end of the fallow after sorghum and just prior to sowing wheat on undisturbed nearly level plot areas. Cistern stored rainwater [pH of 7.3, electrolyte concentration of 16.0 mg kg^{-1}, and an SAR of 0.02 $(mmol\ l^{-1})^{-1/2}$] was applied at a rate of 48 mm h^{-1} using a rotating-disk rainfall simulator with an impact energy of 22 J mm^{-1} m^{-2} (Morin et al., 1967) until a relatively constant infiltration rate had been achieved. This intensity approximates the 40 mm h^{-1} average 60 m duration rainstorm in this region (Frederick et al., 1977) with impact energy of approximately 80% of natural rainfall. The infiltration measurement was centered between wheel tracks (when present) and contained within a 1.5 m square (area = 2.25 m^2) by 0.2 m high metal frame pressed 50 mm into the soil. Runoff water captured by the frame was removed by a peristaltic pump and collected in a graduated cylindrical tank for measurement during rain simulation. Infiltration, calculated as the difference between

Table 1
Chemical weed control applications for the NT residue management system used with the 3-year WSF rotation at Bushland, TX

WSF rotation sequence stage	Chemical application
Fallow wheat harvest (July-Y1)	3.36 kg a.i. ha^{-1} atrazine[a], 0.84 kg a.i. ha^{-1} 2,4-D[b]
Before sorghum planting (June-Y2)	0.56 kg a.i. ha^{-1} glyphosate[c]
Seasonal weed control in sorghum (June-Y2)	1.68 kg a.i. ha^{-1} propazine[d]
Mid-fallow sorghum (February-Y3)	0.023 kg a.i. ha^{-1} chlorosulfuron[e], 0.37 kg a.i. ha^{-1} 2,4-D
Before wheat planting (October-Y3)	0.56 kg a.i. ha^{-1} glyphosate
Any weed control during fallow periods	0.56 kg a.i. ha^{-1} glyphosate, 0.37 kg a.i. ha^{-1} 2,4-D

[a] 6-Chloro-*N*-ethyl-*N*′-(1-methylethyl)-1,3,5-triazine-2,4-diamine.
[b] 2,4-Dichlorophenoxy acetic acid.
[c] *N*-phosphonomethyl glycine.
[d] 6-Chloro-*N*,*N*′-bis (1-methylethyl)-1,3,5-triazine-2,4-diamine.
[e] 2-Chloro-*N*[[(4-methoxy-6-methyl-1,3,5-triazine-2-yl)amino]carbonyl] benzenesulfonamide.

applied water and collected runoff, was measured. Infiltration rate data, recorded as a function of applied water depth, were fitted using nonlinear regression methods described by Baumhardt et al. (1990). Treatment effects on infiltration rate and amount after 48 mm of applied rain (60 min) were compared according to the randomized complete block analysis of variance using SAS-PROCGLM (SAS, 1988).

2.3. Soil characterization

Soil was characterized concurrently with infiltration measurements on similarly positioned nearby areas (<3.0 m away) equidistant from any wheel tracks or tool-shank paths. Gravimetric water content and bulk density were determined to a depth of 0.9 m using undisturbed 5.4 cm inside diameter-slotted tube core samples (Jones et al., 1994). Cone penetration resistance was measured according to the methods of Unger and Jones (1998) to a depth of 0.27 m using a manually operated penetrometer that recorded the resistance with depth (Bush Soil Penetrometer SP10, Findlay Irvine, Penicuik, UK). Soil surface random roughness was determined before and after rain simulations (Allmaras et al., 1966) and, with the same pins used to determine the random roughness, we also determined the percent residue cover taken as the fraction of residue "hits" before rain application using the procedures of Jones et al. (1994). Soil crust strength was measured between rows 6 days after rain application (24 observations per treatment site) using the penetration resistance of a 4.76 mm diameter flat point handheld penetrometer (Model 719-5 MRP, John Chatillon and Sons, Kew Garden, NY).

3. Results and discussion

3.1. Penetration resistance

Soil penetration resistance for SM and NT residue management systems with NOPT, PT and ST tillage is plotted with depth in Fig. 2. Typically, SM loosened the soil to 0.10 m depth, which reduced the penetration

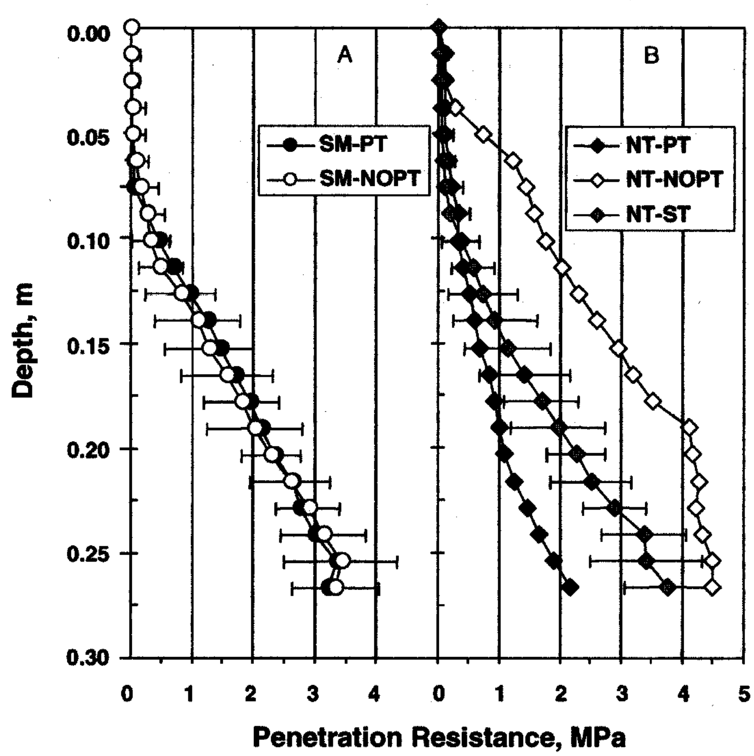

Fig. 2. Mean soil penetration resistance plotted with depth for stubble mulch (SM) residue management plots receiving NOPT and PT (A) and NT residue management plots receiving NOPT, PT, and ST (B). Error bars represent the common LSD ($P < 0.05$) by depth for all treatments.

Table 2
Treatment mean, ±S.D., for the 0.27 m profile penetration resistance (PR), bulk density (BD) to 0.9 m, infiltration rate (IR) and amount (IA, mm), residue cover (RC), random roughness (RR), and crust strength (CS) in stubble mulch, SM, and no-tillage, NT, residue management plots receiving paratillage (PT), no-paratillage (NOPT), and sweep tillage (ST)

Treatment	PR (MPa)	BD (Mg m^{-3})	IR (mm h^{-1})	IA (mm)	RC (%)	RR initial (mm)	RR rain (mm)	CS (MPa)
SM–NOPT	1.16 ± 1.16	1.49 ± 0.11	12.2 ± 6.1	34.4 ± 3.6	24.8 ± 7.4	22.6 ± 5.2	16.9 ± 4.9	0.48 ± 0.21
SM–PT	1.20 ± 1.15	1.43 ± 0.22	11.7 ± 4.0	31.2 ± 2.9	21.9 ± 2.9	22.8 ± 3.3	18.1 ± 0.7	0.86 ± 0.86
NT – NOPT	2.21 ± 1.54	1.52 ± 0.2	10.2 ± 2.6	19.2 ± 4.6	33.3 ± 3.6	17.6 ±3.9	16.8 ± 2.6	0.51 ± 0.18
NT – PT	0.65 ± 0.60	1.46 ± 0.19	10.7 ± 2.8	23.1 ± 2.3	34.5 ± 11.6	22.6 ± 7.9	17.8 ± 2.7	0.41 ± 0.24
NT –ST	1.13 ± 1.18	1.46 ± 0.20	7.7 ± 2.0	18.4 ± 3.1	32.1 ± 9.1	18.8 ± 5.1	16.7 ± 5.8	0.41 ± 0.24
LSD[a] $P = 0.05$	0.07	0.06	5.1	4.4	10.2	9.1	4.8	0.04

[a] Least significant difference within column.

resistance to that depth regardless of the PT treatment (Fig. 2A). Penetration resistance at depths greater than 0.10 m, however, was unexpectedly similar for the PT and NOPT plots receiving SM. The peak penetration resistance measured over the entire 0.27 m profile depth for SM residue management did not exceed 3.5 MPa and averaged about 1.2 MPa with PT and 1.16 MPa with NOPT (Table 2). Under the conditions of our test, soil consolidation below the SM tillage depth apparently developed within the 9 months following PT treatment during fallow after sorghum. That is, any beneficial PT effects to reduce profile penetration resistance were rapidly negated. The benefits of deep tillage to reduce soil density and/or penetration resistance in these soils are often lost through the normal process of soil consolidation (Unger, 1993; Baumhardt et al., 1993). While not measured in this experiment, similar soil compaction resulting from SM during fallow after wheat could be expected.

Penetration resistance in the NT–NOPT plots (Fig. 2B) increased rapidly below 0.05 m depth to a maximum resistance of about 4.5 MPa and was significantly greater than measured for SM–PT or SM–NOPT plots. Peak penetration resistance in NT–PT plots was ~2.1 MPa and averaged 0.65 MPa (Table 2), which was significantly lower than NT–NOPT. Also, PT significantly reduced NT penetration resistance at depths greater than about 0.10 m (Fig. 2) when compared to the apparently compacted SM. Mean 0.27 m profile penetration resistance for NT plots receiving one ST tillage operation was not significantly different from either SM tillage treatment (Table 2) and varied almost identically with depth (Fig. 2). The sweep tillage effect to increase penetration resistance in both SM and NT–ST residue management systems compared to the NT–PT treatment illustrates how rapidly the soil profile was compacted below the tillage implement. The effect of PT to reduce penetration resistance for more than 9 months was significant for the NT residue management system and could promote increased overall water availability through deeper rooting.

3.2. Soil bulk density and water content

Mean soil bulk densities measured 9 months after applying the PT, NOPT, and ST treatments are plotted with depth for SM and NT residue management plots (Fig. 3). Paratillage typically reduces soil bulk density of the tilled layer without significantly affecting residue cover, but a similar reduction in soil bulk density was expected to a shallower, 0.1 m, depth with ST tillage. Our data show that measured soil density near the surface, 0–0.10 m depth, was reduced significantly ($P < 0.05$) when ST or PT were used with both SM and NT. However, PT to depths approaching 0.30 m resulted in no significant reduction in mean soil profile bulk density below 0.15 m for any SM or NT treatment combination. Unlike penetration resistance measurements that showed PT loosened the NT soil profile, the corresponding soil density with depth was not significantly reduced by PT.

When averaged across the various tillage treatments, residue management practices did not significantly affect the mean soil 0.9 m profile density (Table 2). That is, mean soil profile bulk density averaged 1.48 Mg m^{-3} for NT and 1.46 Mg m^{-3} for

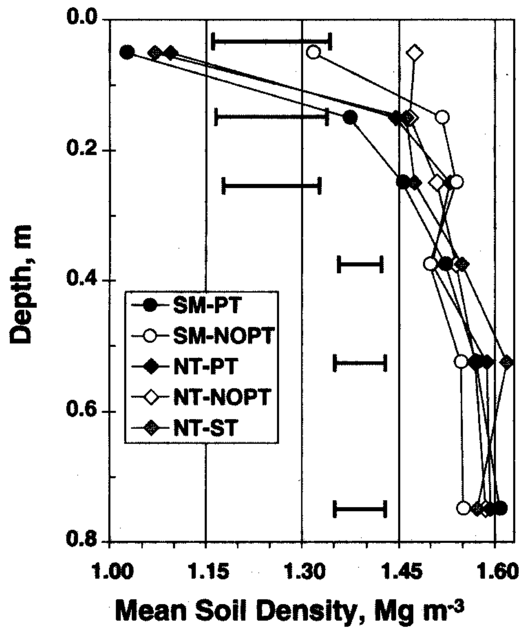

Fig. 3. Mean soil bulk density plotted with depth for SM (circles), and NT (diamonds), residue management plots receiving PT (filled), NOPT (open), and a single ST (shaded). Bars represent the least significant difference by depth.

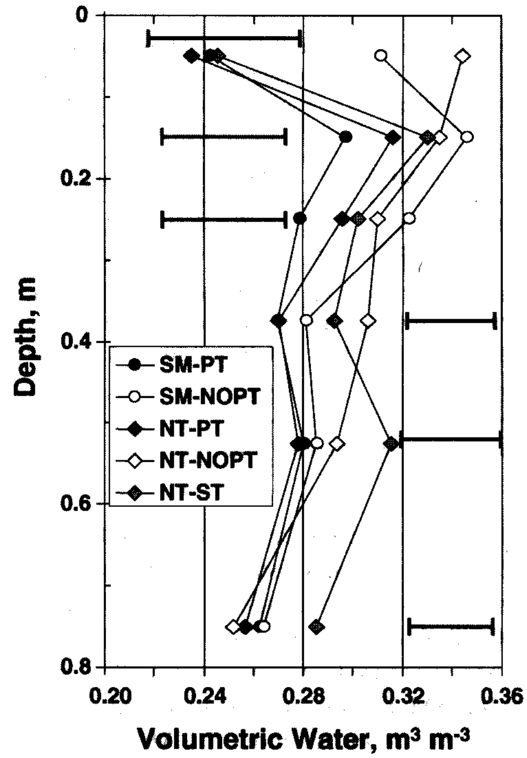

Fig. 4. Volumetric soil-water content plotted with depth for SM (circles), and NT (diamonds), residue management plots receiving PT (filled), NOPT (open), and a single ST (shaded). Bars represent the least significant difference by depth.

SM residue management combinations. The corresponding average profile soil-water contents were, likewise, similar between NT ($\sim$0.29 $m^3\,m^{-3}$) and SM ($\sim$0.29 $m^3\,m^{-3}$) residue management combinations. The mean soil density at the 0–0.10 m depth tended to be less with SM than with NT, but even the largest of these differences with NOPT were not significant (Fig. 3.). The formation of a tillage pan layer with SM or response to the loosening effects of PT on NT soil was not apparent from the bulk density with depth. Volumetric soil water content (Fig. 4) was, however, lower with tillage combinations that reduced soil density. Tillage that increases macropore number and, probably, pore continuity to the surface may, consequently, permit greater evaporation. The corresponding reduction in soil-water content from the surface 0.15 m depth indicated greater evaporation due to tillage. However, a general trend of declining soil-water content and generally increasing soil density with depth below 0.15 m for all tillage practices suggests that, after 9 months, the combined tillage and residue management affects on soil bulk density and water content were confined to the surface 0.15 m depth.

3.3. Rain infiltration

The effects of residue management and tillage combinations on mean infiltration rate (IR) are plotted in Fig. 5 as a function of cumulative applied rain. IR declined much more rapidly with NT than with SM tillage, resulting in runoff after about 4 mm of rain from NT plots compared to about 13 mm of rain required for runoff initiation from SM plots. Once runoff began, however, the mean IR in both NT and SM plots declined rapidly. The IR after $\sim$48 mm applied rain was 9.5 mm h^{-1} with NT compared to 11.9 mm h^{-1} for SM residue management (Table 2) and further declined to quasi-steady final infiltration rates of 8 mm h^{-1} for NT compared to 5 mm h^{-1} for SM plots (Fig. 5). Because the residue cover provided by dryland crops does not completely protect the soil surface from raindrop impact, rapidly forming surface crusts governed infiltration independently of the residue management practices used.

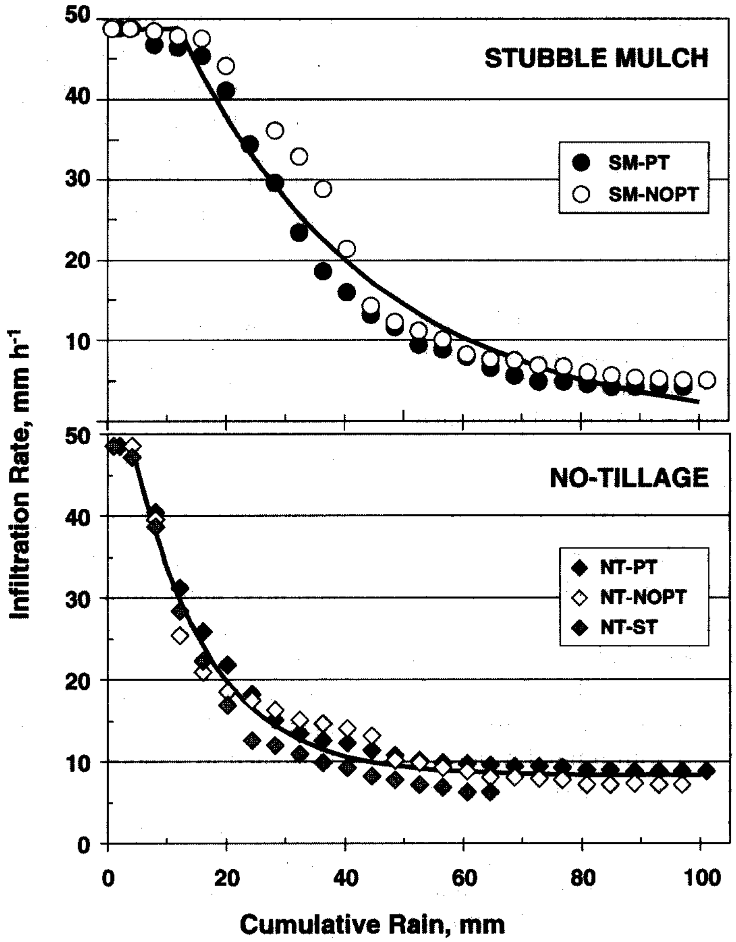

Fig. 5. Mean IR plotted as a function of cumulative rain applied for SM (circles), or NT (diamonds), residue management plots receiving PT (filled), NOPT (open), and a single ST (shaded).

While the use of ST and PT significantly reduced surface soil bulk density compared to NOPT in NT residue management, the anticipated differences in runoff initiation or IR were not observed. Similarly, infiltration into SM–PT was not different from that measured for SM–NOPT. Comparison of IR at ~48 mm rain into the SM and NT combinations with NOPT was not significantly different ($P < 0.05$) from the corresponding PT or ST tillage combinations (Table 2). The absence of a soil crust and increased surface porosity delayed runoff from SM compared to NT residue management plots, but profile modifying tillage used with either residue management practice did not reduce runoff. Because final infiltration rates were not significantly different among combinations of tillage within residue management practices, we conclude that IR was regulated at the soil surface by the presence or rapid formation of a soil crust.

The corresponding measured infiltration amount (IA) after applying 48 mm rain varied significantly because of residue management, i.e., the IA of 21.9 ± 2.5 mm for NT was significantly less than the 32.4 ± 3.9 mm observed for SM. As observed for IR, no significant difference in IA resulted from ST or PT compared to NOPT for either NT or SM residue management. The absence of significant differences between PT and NOPT treatments suggest that, under the conditions of our test, rain infiltration was not governed by the soil profile characteristics, unlike that reported for ponded infiltration (Mukhtar et al., 1985; Clark et al., 1993). During infiltration measurements into chisel tilled soil, Baumhardt et al.

(1993) reported reduced infiltration due to rapid formation of surface crusts and soil profile reconsolidation.

3.4. Residue cover, random roughness and crust strength

Normally, IR and amount increase as residue cover available to intercept raindrop impact and reduce soil crust formation increases (Baumhardt and Lascano, 1996). While both SM and NT retain residues at the soil surface, SM retained on average a 23.3% residue cover compared to 33.3% for NT. As noted previously, infiltration was lower for NT combinations compared to SM. Residue cover did not vary significantly for the SM or NT combinations with PT or ST practices that incorporate limited residue amounts (Table 2). Because of greater residue cover in NT, we expected more raindrop interception with NT compared to SM residue management practices independent of the tillage practices used. As a result, soil surface roughness after a 9-month fallow or immediately following rain would, probably, be less with limited residue.

Random roughness (RR) of the soil surface measured before rain application shows the integrated effects of tillage and residue cover on soil surface weathering. The surface RR ranged from a minimum of 17.6 mm for NT–NOPT to a maximum of 22.8 mm for SM–PT or about half of the least significant difference (LSD) (Table 2.). While surface RR tended to be greater with SM residue management compared to NT, we measured no significant tillage and/or residue management effect on surface roughness before applying simulated rain. The RR measured after rain application was reduced due to similar raindrop impact effects on smoothing surface soil aggregates independent of either residue or tillage treatments. The range in RR narrowed from a minimum of 16.7 mm for NT–ST to a maximum of 18.1 mm for SM–PT (Table 2). The absence of tillage and residue management effects on roughness was attributed to the very similar residue cover provided by grain sorghum integrated over the weathering events during fallow.

Soil crust strength measured 6 days after rain application did not vary consistently with residue management or tillage treatment (Table 2). Crust strength with NT residue management tended to be less than with SM, possibly, because greater residue cover with NT intercepted raindrop impact and decreased soil crust formation. No other consistent pattern emerged from the crust strength measurements in the more variable SM plots. But, NT combinations with PT and ST tillage reduced crust strength compared to NT–NOPT treatments.

4. Conclusions

After 9 months, NT–PT and NT–ST reduced penetration resistance compared to NT–NOPT; however, penetration resistance with depth in the SM plots was largely unaffected by PT. Multiple sweep tillage operations with SM management during fallow after sorghum apparently formed a compacted subsurface soil layer and eliminated macropore channels formed by PT treatment. Infiltration of simulated rain was unaffected by PT of the Pullman clay loam, but rain infiltration with SM residue management was greater than with NT plots. Differences in infiltration were attributed to a more rapidly developing soil crust on the NT managed plots. We conclude that because rain infiltration was rapidly regulated at the soil surface by the formation of a crust, that over time PT will not increase infiltration into clay loam soils managed with SM or NT residue systems.

References

Allmaras, R.R., Burwell, R.E., Larson, W.E., Holt, R.F., 1966. Total porosity and random roughness of the interrow zone as influenced by tillage. USDA Conserv. Res. Rep. 7. US-GPO, Washington, DC.

Baumhardt, R.L., Lascano, R.J., 1996. Rain infiltration as affected by wheat residue amount and distribution in ridged tillage. Soil Sci. Soc. Am. J. 60, 1908–1913.

Baumhardt, R.L., Römkens, M.J.M., Whisler, F.D., Parlange, J.-Y., 1990. Modeling infiltration into a sealing soil. Water Resour. Res. 26, 2497–2505.

Baumhardt, R.L., Keeling, J.W., Wendt, C.W., 1993. Tillage and residue effects on infiltration into soils cropped to cotton. Agron. J. 85, 379–383.

Busscher, W.J., Karlen, D.L., Sojka, R.E., Burnham, K.P., 1988. Soil and plant response to three subsoiling implements. Soil Sci. Soc. Am. J. 52, 804–809.

Clark, R.L., Radcliffe, D.E., Langdale, G.W., Bruce, R.R., 1993. Soil strength and water infiltration as affected by paratillage frequency. Trans. ASAE 36, 1301–1305.

Frederick, R.H., Myers, V.A., Auciello, E.P., 1977. Five-to-60 min precipitation frequency for the eastern and central United States. Natl. Oceanic and Atmos. Admin. Tech. Memo. Natl. Weather Serv. NWS HYDRO-35. US Department Com., Washington, DC.

Hauser, V.L., Van Doren, C.E., Robins, J.S., 1962. Comparison of level and graded terraces in the southern High Plains. Trans. ASAE 5, 75–77.

Jones, O.R., Popham, T.W., 1997. Cropping and tillage systems for dryland grain production in the southern High Plains. Agron. J. 89, 222–232.

Jones, O.R., Hauser, V.L., Popham, T.W., 1994. No-tillage effects on infiltration, runoff and water conservation on dryland. Trans. ASAE 37, 473–479.

Morin, J., Goldberg, S., Seginer, I., 1967. A rainfall simulator with a rotating disk. Trans. ASAE 10, 74–79.

Mukhtar, S., Baker, J.L., Horton, R., Erbach, D.C., 1985. Soil water infiltration as affected by the use of the paraplow. Trans. ASAE 28, 1811–1816.

Pikul, J.L., Aase, J.K., 1999. Wheat response and residual soil properties following subsoiling of a sandy loam in eastern Montana. Soil Till. Res. 51, 61–70.

SAS, 1988. SAS/STAT Users Guide, Release 6.03 Edition. SAS Institute, Inc., Cary, NC, 1028 pp.

Steiner, J.L., 1994. Crop residue effects on water conservation. In: Unger, P.W. (Ed.), Managing Agricultural Residues. Lewis Publishers, Boca Raton, FL, pp. 41–76.

Unger, P.W., 1993. Reconsolidation of a Torrertic Paleustoll after tillage with a paratill. Soil Sci. Soc. Am. J. 57, 195–199.

Unger, P.W., Baumhardt, R.L., 1999. Factors related to dryland grain sorghum yield increases: 1939 through 1997. Agron. J. 91, 870–875.

Unger, P.W., Jones, O.R., 1998. Long-term tillage and cropping systems affect bulk density and penetration resistance of soil cropped to dryland wheat and grain sorghum. Soil Till. Res. 45, 39–57.

Unger, P.W., Pringle, F.B., 1981. Pullman soils: distribution, importance, variability, and management. Texas Agric. Exp. Stn. Bull. B-1372, College Station, TX.